Supersplit Supersymmetry and the 750 GeV Diphoton Excess

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(Dated: April 1, 2016)

We examine the scenario of "supersplit supersymmetry" in light of the observed diphoton excess at 750 GeV. We discuss the difficulties of explaining tuning of the model with anthropic arguments alone and propose a new *phenothropic principle*. A brief statistical analysis of the model is conducted including the 2-dimensional look-elsewhere effect in two of the model parameters most relevant for LHC phenomenology. We find that the model is excluded by both ATLAS and CMS at the $2-3\sigma$ level; however, the excess can be accommodated by invoking the phenothropic selection mechanism with a small overall contribution to the tuning of the theory.

I. INTRODUCTION

The ATLAS and CMS collaborations have recently reported an excess in the diphoton invariant mass spectrum at 750 GeV in both of the 8 and 13 TeV data sets [1, 2]. The possibility that this is the new physics holy grail we have been seeking has sent the theoretical community into a frenzy [3]. We will refer to this putative particle with the Greek letter `\digamma` $\digamma$ [29].

Of course, the discovery of the Higgs boson at 125 GeV brought to the forefront the issue of naturalness and fine tuning [4, 5]. The arrival of the $\digamma$ motivates reexamination of finely tuned theories. Let us briefly revisit the history and motivation of this paradigm. The realization that the broad string landscape may have an exponentially large number of metastable vacua [6–8] supported Weinberg's anthropic argument for a solution to the cosmological constant problem based upon a scan over many possible universes [9]. Agrawal *et. al* [10] and later Arkani-Hamed and Dimopoulos [11] argued that similar scanning may be relevant for weak scale physics. In "split supersymmetry", all but one scalar of the many scalars in the minimal supersymmetric standard model (MSSM) are given very large masses. One linear combination of the two scalar superpartners of the Higgsinos remains light and then acquires a vacuum expectation value (vev) which breaks electroweak symmetry and gives masses to the weak gauge bosons. The fermion masses, which can be protected by symmetries, remain small.

Fox, *et. al.* [12] took the next logical extension by decoupling both Higgsinos and the gauginos in a model they call "supersplit supersymmetry". The low energy effective theory consists of $SU(3)\times SU(2)\times U(1)$ gauge fields and three generations of quarks and leptons, as well as one scalar (whose mass is tuned to be light) which is responsible for electroweak symmetry breaking. The Lagrangian for this model is simply

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4g_1^2}W_{\mu\nu}W^{\mu\nu}-\frac{1}{4g_2^2}B_{\mu\nu}B^{\mu\nu}-\frac{1}{4g_s^2}G_{\mu\nu}G^{\mu\nu}\\ &+\;\bar\psi_f(i\gamma^\mu D_\mu-m_f)\psi_f+D_\mu hD^\mu h^*-V(h)\end{aligned}\tag{1}$$

where f indexes the various fermions, and D is the appropriate covariant derivative. The spectrum of split and supersplit supersymmetry are shown in Fig. 1.

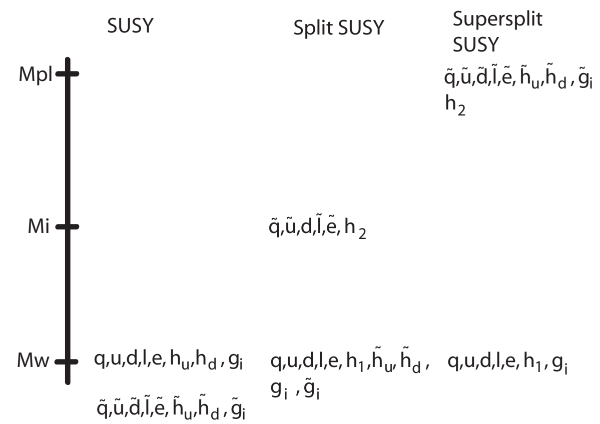

FIG. 1: Mass scales in the MSSM, split SUSY and supersplit SUSY. Taken from Ref. [12].

The addition of the $\digamma$ changes this picture and once again pulls us back into the era in which the phenomenological consequences of additional fields must be studied. As was highlighted by Ref. [13] it is difficult to accommodate additional scalars and address naturalness without resorting to awkward mechanisms. On the other hand, while the so-called "atomic principle" [10] has been used as part of an anthropic argument for fine tuning of the weak scale, this does not carry over to the unexpected $\digamma$ resonance. Thus, we seek a new principle that can address this additional source of tuning.

II. THE PHENOTHROPIC PRINCIPLE

Already in Ref. [12], Fox, *et. al.* argued that the existence of fine tuning in nature dramatically increases the time scale over which fundamental physical laws are discovered. Since the rapid discovery of fundamental laws is strongly correlated with the advance of technologies that might lead to the destruction of civilization, this should be taken into account in the Drake equation. In short, a universe without fine-tuning, theoretical physics may not be possible. [30]

Here we consider a variant of this idea. Instead of the ill-defined notion of "theoretical physics", we employ a more quantitative measure, namely the number of papers submitted to the arXiv. Recently, a quantitative model for the number of papers covering an unexpected result was proposed [16]. In particular, the number of papers as a function of time was derived from a compounded Poisson process leading to a di-gamma function $\mu_N(T)$ [31].

Next we follow the logic of the anthropic principle, which can schematically be written using Bayes theorem as

$$p(\text{universe}\mid\text{us}) \propto \underbrace{p(\text{us}\mid\text{universe})}_{\text{anthropic selection}}\, p(\text{universe})\,. \qquad (2)$$

We highlight the term $p(\text{us}\mid\text{universe})$ that is the mechanism for anthropic selection. By analogy we introduce the *phenothropic principle*, which can schematically be written

$$p(\text{excess}\mid\text{papers}) \propto \underbrace{p(\text{papers}\mid\text{excess})}_{\text{phenothropic selection}}\, p(\text{excess})\,. \qquad (3)$$

The term $p(\text{papers}\mid\text{excess})$ is a new selection mechanism addressed by Ref. [16], while $p(\text{excess})$ is the subject of more traditional statistical analysis and the following section.

III. STATISTICAL CONSIDERATIONS

The ATLAS and CMS collaborations have quantified the statistical significance of the excess in the $m_{\gamma\gamma}$ spectrum under a both spin-0 and spin-2 hypotheses. The local significance for the 13 TeV data under the spin-0 hypothesis stands at 3.9σ and 2.9σ, for ATLAS and CMS respectively. Of course, we do not know the mass of the resonance a priori, so one must correct for the look-elsewhere effect [17]. After this correction, the global significance for ATLAS is around 2σ and even less for CMS. While a heuristic approach would be to say that one experiment tells you where too look, and the other provides the statistical evidence. This approach violates an obvious permutation symmetry and has been criticized recently [18]. A more careful treatment would be to combine first and then correct for the look-elsewhere effect on the combination (see Ref. [19] for more details). While the objection to the heuristic approach is a good one in principle, in this particular case it does not make a very large quantitative difference.

Perhaps more interesting is the issue of the 5σ discovery threshold. As discussed in Cousins's tome on the Jeffreys-Lindley Paradox (see the section on *the mythology of* 5σ) the arbitrary 5σ convention was adopted as an ad hoc way of protecting against the look-elsewhere effect [20]. To use 5σ threshold after correcting for the look-elsewhere effect is both arbitrary and breaking from the historical convention. A more rational motivation for the lack of desire to claime a discovery at this point

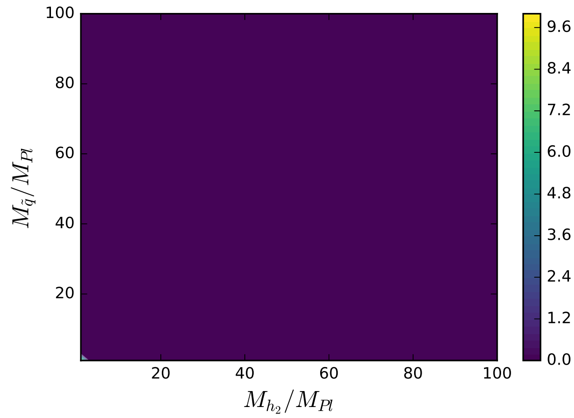

FIG. 2: Plot of $q(M_{h_2}, M_{\tilde{q}}) = -2\ln\lambda(M_{h_2}, M_{\tilde{q}})$.

is that the prior degree of belief in this unexpected resonance is low, the risk associated to a false discovery is high, and the time needed to collect enough data to make a more conclusive statement is short.

Another issue that comes up in the statistical analysis of $\digamma$ is that the data prefer a wide resonance. This leads to a look-elsewhere effect in both the mass and width of the resonance. We briefly review the methodology used by ATLAS as described in a beautiful work by Vitells and Gross [21]. In this formalism we have a likelihood function of the form $L(\mu, \nu_1, \nu_2)$ where μ is a signal strength parameter proportional to $\sigma \times Br$ and ν_1, ν_2 are the unknown mass and width of the new particle. Next one performs the search by scanning over ν_1 and ν_2 and calculating the test statistic [22]

$$q(\nu_1, \nu_2) = -2\log\frac{\max_\theta L(\mu = 0, \nu_1, \nu_2, \theta)}{\max_{\mu,\theta} L(\mu, \nu_1, \nu_2, \theta)} \qquad (4)$$

The LEE correction in this case is based on

$$E[\phi(A_u)] = P(\chi^2_1 > u) + e^{-u/2}(N_1 + \sqrt{u}N_2) \qquad (5)$$

where A_u is the 'excursion set above level u (eg. the set of parameter points in (ν_1, ν_2) that have a $q(\nu_1, \nu_2) > u$), $\phi(A_u)$ is the Euler characteristic of the excursion set, $E[\phi(A_u)]$ is the expectation of the Euler characteristic of those excursion sets under the null, $P(\chi^2_1 > u)$ is the standard chi-square probability , and N_1 and N_2 are two coefficients that characterize the chi-square random field.

Now we repeat, for the first time, this 2-d LEE correction for a new physics model description of the $\digamma$ excess. Instead of scanning over the mass and width of a generic spin-0 or spin-2 particle, we scan over two high-scale parameters of the supersplit supersymmetry model. We perform this scan for many pairs of the model parameters. Figure 2 shows the scan with respect to M_{h_2} and $M_{\tilde{q}}$. We find the coefficients $N_1 = N_2 = 0$, thus in the case of supersplit supersymmetry the 2-d look-elsewhere effect is negligible.

While the correction for look-elsewhere effect is negligible, the test statistic $q(M_{h_2}, M_{\tilde{q}}) = 0$ within numerical precision for all $M_{h_2}, M_{\tilde{q}}$. This indicates that the likelihood ratio isn't a powerful test statistic for the case of supersplit supersymmetry against the standard model null hypothesis. Instead, we employ a number of goodness-of-fit statistics, including a simple binned chi-square by digitizing the plots from the slides on the Moriond agenda page. We find that the supersplit supersymmetry model is not a good fit to the data and p-values compatible with the background-only p-values reported by ATLAS and CMS. Thus we can exclude supersplit supersymmetry at the $2-3\sigma$ level.

Alternatively, one might consider the Bayes factor

$$B_{10} = \frac{\int p_{\rm SSSS}(x|\nu)\pi(\nu)d\nu}{p_{\rm SM}(x)} \ , \tag{6}$$

where $p_{\rm SSSS}(x|\nu)$ is the likelihood of the data under the supersplit supersymmetry model with high-scale parameters ν, $\pi(\nu)$ is the prior over those high-scale parameters, and $p_{\rm SM}(x)$ is the likelihood of the data under the standard model hypothesis (where we treat all the low-scale parameters fixed). We find in all cases studied that $B_{10} \approx \int \pi(\nu)d\nu \approx 1$ to a good approximation. Unlike the frequentist goodness-of-fit test, the Bayesian analysis does not disfavor the supersplit model and accounts for the large prior volume in the high-scale parameters, which is one of the main advantages according to advocates of Bayesian statistics.

IV. CONCLUSIONS AND OUTLOOK

At face value the likelihood $p_{\rm SSSS}(\text{excess})$ is quite small, thus it is an interesting possibility that phenothropic selection pressure could be the mechanism that reconciles the unusual result conditional on the observed number of papers. This comes at an increased level of tuning; however, it is a rather small contribution to the overall tuning of the supersplit model.

Conversely this tuning provides a way to indirectly gain evidence that a new principle is at play. Just as the evidence for anthropic tuning grows with the square of the mass scale that we have probed [23] (eg. by going from $M_{\tilde{t}} > 1$ TeV to $M_{\tilde{t}} > 10$ TeV with a 100 TeV collider) , evidence for a phenothropic tuning grows with the square root of the luminosity (for a fixed energy collider). Thus with 3000 fb^{-1} of data at the 13 TeV LHC, the evidence for phenothropic selection could grow by a factor of about 25 compared to the current Run 2 dataset..

While we do not consider it explicitly here, we anticipate that the models in Ref. [24–26] will also need phenothropic selection to be employed. The number of citations to Ref. [24–26] is indirect evidence for this phenothropic hypothesis. Furthermore, these models may reveal an even more minimal model for F than that of Ref. [27]. We anticipate that the model by Dvali et. al. [28] and the newly proposed NNaturallness – both of which try to address naturalness directly – might develop tuning problems in the light of F. The apparent tuning in these models can also be explained by employing the phenothropic selection mechanism.

Finally, we applaud the ATLAS experiment for making available plots of kinematic variables associated to the excess. We encourage this in the future as this information may make it easier to exclude models more quickly and reduce the number of papers on this excess.

[1] The ATLAS collaboration, ATLAS-CONF-2016-018.
[2] CMS Collaboration [CMS Collaboration], CMS-PAS-B2G-16-004.
[3] The number of works focusing on the 750 GeV excess is staggering. If you feel that your work should be specifically cited, please contact the author.
[4] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 doi:10.1016/j.physletb.2012.08.020 [arXiv:1207.7214 [hep-ex]].
[5] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) doi:10.1016/j.physletb.2012.08.021 [arXiv:1207.7235 [hep-ex]].
[6] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi, Phys. Rev. D **68**, 046005 (2003) [arXiv:hep-th/0301240].
[7] L. Susskind, arXiv:hep-th/0302219.
[8] M. R. Douglas, JHEP **0305**, 046 (2003) [arXiv:hep-th/0303194].
[9] S. Weinberg, Phys. Rev. Lett. **59**, 2607 (1987).
[10] V. Agrawal, S. M. Barr, J. F. Donoghue and D. Seckel, Phys. Rev. D **57**, 5480 (1998) [arXiv:hep-ph/9707380].
[11] N. Arkani-Hamed and S. Dimopoulos, arXiv:hep-th/0405159.
[12] P. J. Fox, D. E. Kaplan, E. Katz, E. Poppitz, V. Sanz, M. Schmaltz, M. D. Schwartz and N. Weiner, hep-th/0503249.
[13] P. W. Graham, D. E. Kaplan and S. Rajendran, Phys. Rev. Lett. **115**, no. 22, 221801 (2015) doi:10.1103/PhysRevLett.115.221801 [arXiv:1504.07551 [hep-ph]].
[14] N. Arkani-Hamed, S. Dimopoulos and S. Kachru, arXiv:hep-th/0501082.
[15] K. Cheung and C. W. Chiang, arXiv:hep-ph/0501265.
[16] M. Backović, arXiv:1603.01204 [physics.soc-ph].
[17] E. Gross and O. Vitells, Eur. Phys. J. C **70**, 525 (2010) doi:10.1140/epjc/s10052-010-1470-8 [arXiv:1005.1891 [physics.data-an]].
[18] R. D. Cousins, `https://indico.cern.ch/event/233551/contribution/1/attachments/389867/542286/cousins_look_elsewhere_14feb2013.pdf`
[19] K. Cranmer, `https://github.com/`

cranmer/look-elsewhere-2d/blob/master/two-experiment-lee.ipynb

[20] R. D. Cousins, arXiv:1310.3791 *Synthese* (2013)

[21] O. Vitells and E. Gross, Astropart. Phys. **35**, 230 (2011) doi:10.1016/j.astropartphys.2011.08.005 [arXiv:1105.4355 [astro-ph.IM]].

[22] G. Cowan, K. Cranmer, E. Gross and O. Vitells, Eur. Phys. J. C **71**, 1554 (2011) Erratum: [Eur. Phys. J. C **73**, 2501 (2013)] doi:10.1140/epjc/s10052-011-1554-0, 10.1140/epjc/s10052-013-2501-z [arXiv:1007.1727 [physics.data-an]].

[23] N. Arkani-Hamed, T. Han, M. Mangano and L. T. Wang, arXiv:1511.06495 [hep-ph].

[24] S. Glashow, "Towards a Unified Theory - Threads in a Tapestry," Nobel Lecture, Dec 8, 1979.

[25] A. Salam, "Gauge Unification of Fundamental Forces," Nobel Lecture, Dec 8, 1979.

[26] S. Weinberg, "Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions," Nobel Lecture, Dec 8, 1979.

[27] C. Csáki, J. Hubisz and J. Terning, Phys. Rev. D **93**, no. 3, 035002 (2016) doi:10.1103/PhysRevD.93.035002 [arXiv:1512.05776 [hep-ph]].

[28] G. Dvali and M. Redi, Phys. Rev. D **77**, 045027 (2008) doi:10.1103/PhysRevD.77.045027 [arXiv:0710.4344 [hep-th]].

[29] We thank David Pinner for his classics expertise.

[30] A quantitative assessment of this claim is *still* forth coming

[31] We note the particularly good fit of the di-gamma model to the citation history of ATLAS and CMS $\digamma$ papers. Cosmic coincidence? We think not.